Direct Phase-Resolved Simulation of Large-Scale Nonlinear Ocean Wave-Field

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LONG-TERM GOAL

The long-term goal is to develop a new powerful capability, which is named **SNOW** (**s**imulation of **n**onlinear **o**cean **w**ave-field), for predicting the evolution of large-scale nonlinear ocean wavefields using direct phase-resolved simulations. Unlike the existing phase-averaged approaches, SNOW models the key mechanisms such as nonlinear wave-wave, wave-current, wave-wind and wave-bottom interactions and wave-breaking dissipation in a direct physics-based context.

OBJECTIVES:

The specific scientific and technical objectives are to:

1. Continue to develop and improve physics-based phenomenological modeling for wind forcing input and wave breaking dissipation.

2. Extend SNOW capabilities to handle high sea states for investigating the effect of very steep local waves upon evolution of wave statistics of nonlinear wavefields.

3. Speed up the computational algorithm underlying SNOW simulations for large spatial-temporal scale wavefields to enable more direct comparisons to phase-averaged models and certain observations.

4. Obtain direct validation and quantitative cross-calibration of SNOW simulations with phase-averaged wave model predictions and field/laboratory measurements.

5. Extend SNOW to general finite water depth by including effects of bottom dissipation, fluid stratification, and variable current and bottom topography.

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APPROACH

SNOW employs direct physics-based phase-resolved simulations for predicting the evolution of large-scale nonlinear ocean wavefields. SNOW is fundamentally different from the existing phase-averaged models in that, under SNOW, key physical mechanisms such as wave-current, wave-wind and wave-bottom interactions and wave-breaking dissipation are modeled, evaluated and calibrated in a direct physics-based context. In SNOW, detailed phase-resolved information about the wavefield is obtained, from which the statistical wave properties can also be derived.

SNOW is based on an extremely efficient high-order spectral (HOS) approach for direct computation of nonlinear ocean wavefield evolution. HOS is a pseudo-spectral-based method that employs Zakharov equation and mode-coupling idea and accounts for nonlinear wave-wave, wave-current, and wave-bottom interactions to an arbitrary high order (M) in wave steepness. This method is highly efficient as it obtains exponential convergence and (approximately) linear computational effort with respect to M and the number of spectral wave/bottom modes (N). HOS is an ideal approach for direct phase-resolved simulations of nonlinear ocean wavefield evolution in a large space-time domain. The efficacy of HOS for the study of mechanisms of nonlinear wave dynamics in the presence of atmospheric forcing, long-short waves, finite depth and depth variations, variable ambient current, and density stratification has been well established (e.g. Mei, Stiassnie & Yue 2005).

For data assimilation and/or specification of initial nonlinear wavefields in direct phase-resolved simulations, an effective nonlinear wave reconstruction algorithm is employed. The objective of wave reconstruction is to obtain detailed specifications (including phase) of a nonlinear wave-field, which matches given wave probe and/or remotely sensed data, or a specified wave spectrum. The scheme for nonlinear wave reconstruction is based on the use of multiple-level optimizations with theoretical and computational solutions for the nonlinear wave dynamics. The validity of this methodology has been systematically verified by quantitative comparisons to laboratory measurements and synthetic wave data for both long- and short-crested irregular wave-fields (Wu 2004; Wu et al 2007a, b).

For large-scale ocean wavefield evolution, SNOW computations are performed on high-performance computing platforms using up to $O(10^3)$ processors.

WORK COMPLETED

The main focuses of the research are on the development and improvement of effective physics-based models for wind forcing input and breaking wave dissipation, extension of SNOW to account for density stratification effect, speedup of SNOW computations on high-performance computing platforms, and validation of SNOW simulations by direct comparisons against laboratory experiments and field measurement. Specifically,

- ***Wave breaking mechanism and dissipation model***: We investigated the basic mechanisms governing the development of three-dimensional wave breaking phenomena. Based on the understanding of wave breaking phenomena, we developed and applied effective physics-based phenomenological modeling of wave breaking dissipation in phase-resolved (SNOW) simulation of three-dimensional nonlinear ocean wavefield evolution. The effectiveness of the modeling was verified by comparisons of SNOW computations to the existing laboratory experiments of wave focusing and grouping as well as (three-dimensional) steep crescent wave evolution.

- ***Modeling of wind forcing input***: Generation and growth mechanisms of wind waves were studied in the context of phase-resolved wavefield simulation. The wind forcing is modeled as an external surface pressure on ocean waves in SNOW simulations. The distribution of the surface pressure, which is affected by the interaction of the progressive waves with the wind, is parameterized according to the sheltering theory by adjustment to the observed spectral growth rates. The specific details of the nonlinear response of the wave field to this forcing are quantitatively investigated using SNOW computations and compared to existing experiments. Based on this mechanistic study, we developed an effective modeling of wind forcing for large-scale SNOW computations of ocean wavefield evolution.
- ***Modeling of stratified fluid and bottom topography effects***: We extended SNOW simulations to littoral zones including stratified fluid and bottom topography effects. To consider the density stratification effect, SNOW was extended to multi-layer fluids. The resonant interactions among surface waves, interfacial waves, and bottom ripples were extensively investigated. The study provides an understanding of alternate mechanisms for the generation of internal waves in the ocean, and established a framework for large-scale phase-resolved computations of internal wavefield evolution and interaction with surface waves (Alam, Liu & Yue 2007a, b).
- ***Efficient algorithm for steep waves***: We developed a highly efficient computational algorithm, so-called pre-corrected FFT method, for the simulation of fully-nonlinear steep wave dynamics. This approach is based on the boundary-element method formulation with the use of FFT algorithm for efficient evaluation of influence coefficients (Yan, Liu & Yue 2006). While much more complex in implementation, the PFFT algorithm requires ~O(N) computational effort, similarly to HOS. This algorithm is a useful complementary to SNOW for resolving extreme wave events developed in large-scale ocean wavefield evolution.
- ***Speedup of SNOW***: We continued to seek for high-performance computational resources to support the SNOW project. Last year, we were awarded a DoD challenge project to support SNOW computations and development. We constantly improved the computational speed, scalability and robustness of the SNOW code on high-performance computing platforms.
- ***Wave spectrum evolution by SNOW simulations***: We continued to perform large-scale phase-resolved SNOW computations for predicting wave spectrum evolution and compare the SNOW results with the phase-averaged model predictions for cross validation.

RESULTS

The understanding of characteristics of nonlinear ocean wavefield is of great interests to navy ship design and naval operation. We applied SNOW simulations to obtain data sets on phase-resolved nonlinear evolution of large-scale ocean wavefields, from which we analyzed the spectral and statistical characteristics of such wavefields. We found that (i) nonlinear ocean wavefields exhibit frequency-dependent angular spreading with bi-modal spreading for short wave components; and (ii) the wavenumber spectrum of nonlinear ocean wavefieds exists an equilibrium form in the range of high wavenumbers and the spectrum decays like $k^{-2.5}$ for short waves. SNOW simulations capture these features in agreement with field observations.

For SNOW simulations, we consider a three-dimensional wavefield initially given by a JONSWAP spectrum with $\cos^2$-type directional spreading function. The parameters of the spectrum are: significant wave height H_s=10m, peak wave period T_p=12s, Phillips parameter α=0.0081, peak enhancement coefficient γ=3.3, and angular spreading width Θ=4π/9. The computational domain of 30km × 30km is used for SNOW simulations. The other computational parameters are: order M=3, number of wave modes N=2.1 ×10^6, and time step $\Delta t = T_p/64$. For each simulation, we specify the initial conditions by matching a nonlinear wavefield to the prescribed wave spectrum through an iterative procedure. The SNOW simulation of nonlinear evolution is stopped after the wavefield is evolved for $150T_p$.

Directional spreading: It has been believed for a long time that the directional spreading of an ocean wavefield is unimodal. However, recent field measurements indicate that the wave energy for short waves (i.e. large wavenumber/frequency) exhibits a bi-modal feature, i.e. most of the wave energy is in two major directions symmetric about the main propagation direction of the wavefield (e.g. Ewans 1998; Hwang & Wang 2000). In order to verify the existence and investigate the generation mechanism of such bi-modal directional spreading feature, we compute the normalized direction spreading function for different wavenumber from the SNOW simulation results at t=$150T_p$. The results are shown in figure 1, compared with the field measurements. The SNOW results indicate that the directional spreading behaves like a unimodal function for wave components with wavenumbers near the peak wavenumber (k_p) while it changes to a bi-modal function for wave components with wavenumbers much larger than k_p. Such a characteristic feature (obtained from phase-resolved SNOW simulations) agrees very well with field measurements although the detailed wavefield conditions in the SNOW simulation differ from those in field measurements. Importantly, since there is no wind forcing in the simulation and the SNOW simulation is initialized with a uniform unimodal directional spreading function for all wavenumber, it can be concluded that the bi-modal directional spreading feature is a consequence of long-time nonlinear wave-wave interactions.

Spectral slope: Another important controversial in the description of wave spectrum evolution is the decay slope of the spectrum for short waves with wavenumber much larger than k_p. It is generally believed that there exists an equilibrium range within which the wave spectral shape follows a power law. The value of the power is however inconclusive (Komen et al 1994). Recent field measurements indicate that the spectral shape behaves like $k^{-2.5}$ for wave components with wavenumber in between $2k_p$ and $5k_p$ (Hwang et al 2000). In this study, we verified this observation by SNOW computations. Figure 1 shows the spectrum of the nonlinear wavefield obtained in SNOW simulation at t=$150T_p$, compared with the field measurements of Hwang et al (2000). It shows that the omni-directional wave spectrum (from SNOW simulation) does behave like $k^{-2.5}$ for wavenumber in between $2k_p$ and $5k_p$, which agrees with the field observation. Again, since SNOW simulation does not include wind forcing and is initialized with the JONSWAP spectrum (that does not have $k^{-2.5}$ behavior for short waves), we can conclude that nonlinear wave-wave interaction is the key mechanism causing the formation of such a characteristic spectral feature of nonlinear ocean wavefield.

IMPACT/APPLICATIONS

This work is the first step toward the development of a new generation of wave prediction tool using direct phase-resolved simulations. It augments the phase-averaged models in the near term and may serve as an alternative for wave-field prediction in the foreseeable future.

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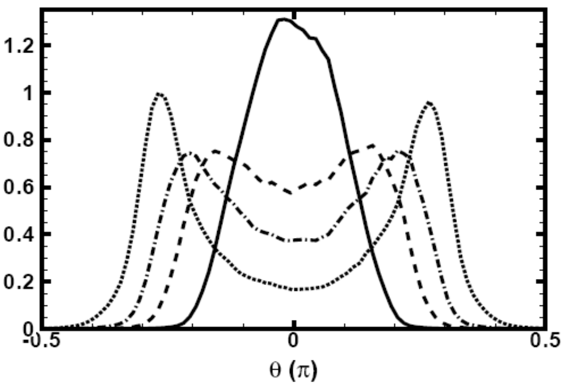
PUBLICATIONS

1. Alam, R.-M., Liu, Y. & Yue, D.K.P. 2007a Bragg resonance of waves on a two-layer fluid propagating over bottom ripples. Part I: Perturbation analysis. *J. of Fluid Mech*. (submitted).
2. Alam, R.-M., Liu, Y. & Yue, D.K.P. 2007b Bragg resonance of waves on a two-layer fluid propagating over bottom ripples. Part I: Numerical simulation. *J. of Fluid Mech*. (submitted).
3. Wu, G., Liu, Y., Kim, M.H. & Yue, D.K.P., 2007 Deterministic reconstruction and forecasting of nonlinear irregular wave fields. *J. of Fluid Mech*. (submitted).
4. Wu, G., Liu, Y., W. Xiao & Yue, D.K.P., 2007 Direct Phase-Resolved Simulations of Nonlinear Evolution of Realistic Ocean Wavefield. *J. of Fluid Mech*. (submitted).



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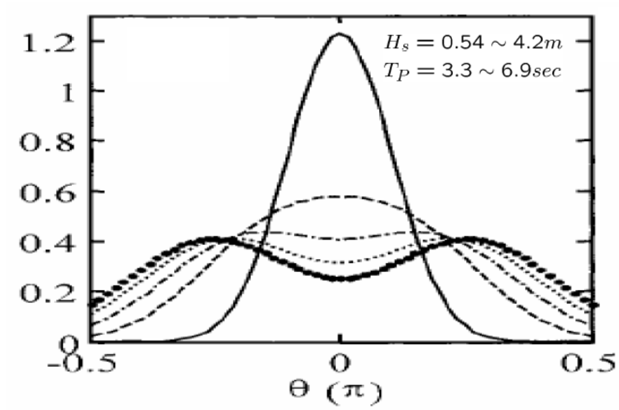

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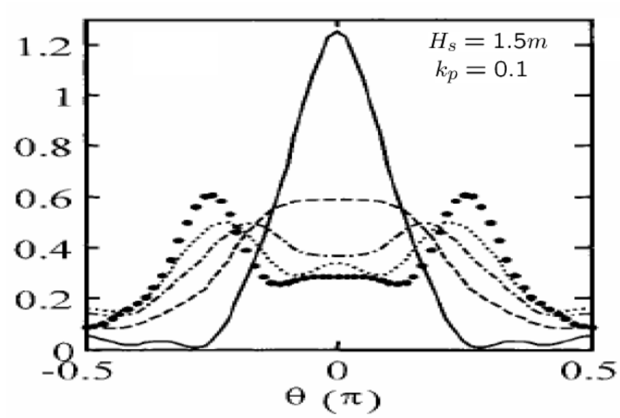
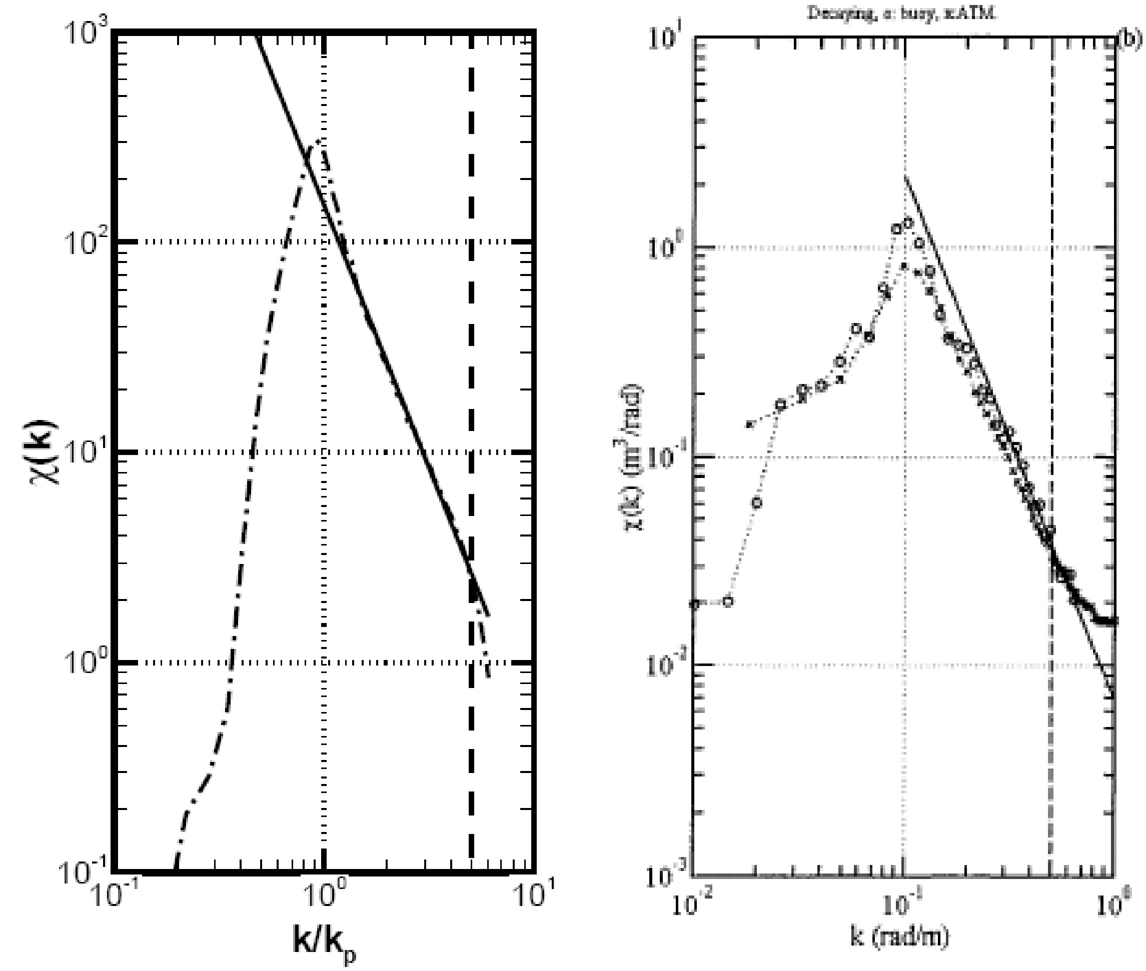


(c)

Figure 1: Dependence of directional spreading function on wavenumber: ——: k/k_p=1; – – –: k/k_p=3; – · – · –: k/k_p=5; · · · · ·: k/k_p=7. Plotted are the results from: (a) direct phase-resolved SNOW simulation (H_s=10m, T_p=12sec); (b) field observation using buoy of Ewans (1998) (H_s=0.54~4.2m, T_p=3.3~6.9sec); and (c) field observation using radar of Hwang & Wang (2000) (H_s=1.5m, T_p=6.3sec). Simulation verifies field observations.



(a) **(b)**

Figure 2: Comparison of the omni-directional wavenumber spectra obtained from (a) SNOW simulation (H_s=10m, T_p=12sec); and (b) field measurement of Hwang et al (2000) (H_s=1.5m, T_p=6.3sec). Plotted curves are: – · – · –: SNOW simulation results; –x–x–: radar measurements; –o–o–: buoy measurements; ——: asymptotic function $k^{-2.5}$. Simulation verifies field observations.